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6. AUTHORS
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14. ABSTRACT
This research, funded by the Department of Defense via the Research and Education Program for Historically Black Colleges and Universities and Minority-Serving Institutions (HBCU/MI), was conducted at the Applied Mechanics and Materials Research Laboratory, Howard University, Washington, DC from May 1, 2011 through October 31, 2014. The overall objective of the project is to develop and implement robust simulation-based strategies for notch root analysis and fatigue life prediction that account for the interactions between the complexity of the material

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					19b. TELEPHONE NUMBER
					202-806-6594

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Report Title

Final Report: Microstructure-Sensitive Fatigue Design of Notched Components

ABSTRACT

This research, funded by the Department of Defense via the Research and Education Program for Historically Black Colleges and Universities and Minority-Serving Institutions (HBCU/MI), was conducted at the Applied Mechanics and Materials Research Laboratory, Howard University, Washington, DC from May 1, 2011 through October 31, 2014. The overall objective of the project is to develop and implement robust simulation-based strategies for notch root analysis and fatigue life prediction that account for the interactions between the complexity of the material microstructures and the notch-root stress gradients. A new probabilistic framework was developed to analyze the fatigue potency of notched specimens in order to improve the prediction of high cycle fatigue of notched components. The probabilistic framework based on Weibull's weakest link and extreme-value statistics was also extended to multiphase materials including titanium alloy and nickel-base super alloys using simulation strategies that capture both the essence of notch root stress gradient and the complexity of realistic microstructures. A new approach which can be applied using crystal plasticity finite element or closed-form solution was also developed as a more robust approach for determining the fatigue notch factor than the existing classical methods.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received		Paper
01/26/2015	19.00	Gbadebo Owolabi, Horace Whitworth. On the concept of fatigue notch factor, JP journal of solids and structures, (05 2012): 63. doi:
01/26/2015	20.00	Gbadebo Owolabi, Horace Whitworth. MICROSTRUCTURALLY SMALL CRACK FORMATIONAND GROWTH IN NOTCHED TURBINE ENGINEMATERIAL, JP journal of solids and structures, (08 2013): 1. doi:
06/19/2012	7.00	Gbadebo Owolabi, Benedict Egboiyi, Li Shi, Horace Whitworth. Microstructure-dependent fatigue damage process zoneand notch sensitivity index, International Journal of Fracture, (08 2011): 159. doi:
08/25/2014	14.00	G.M. Owolabi, H.A. Whitworth. Modeling and Simulation of Microstructurally Small Crack Formation andGrowth in Notched Nickel-base Superalloy Component, Journal of Materials Science and Technology, (09 2013): 203. doi:
08/25/2014	17.00	Mayowa Okeyoyin, Oluwakayode Bamiduro, Horace Whitworth, Gbadebo Owolabi. Extension of a Probabilistic Mesomechanics Based Model forFatigue Notch Factor to Titanium Alloy Components, Procedia materials science, (06 2014): 1860. doi:
08/25/2014	16.00	Gbadebo Owolabi, Mayowa Okeyoyin, Oluwakayode Bamiduro, Horace Whitworth. Fatigue Strength Reduction Factor for Polycrystalline NickelBase Superalloy with and without Non-Metallic Inclusions, Procedia Engineering, (06 2014): 297. doi:
09/12/2013	12.00	Oluwamayowa Okeyoyin. Application of Weakest Link Probabilistic Framework for Fatigue Notch Factor to Turbine Engine Materials , World journal of mechanics, (07 2013): 237. doi:

TOTAL: **7**

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received	Paper
08/25/2014 15.00	Gbadebo Owolabi, Mayowa Okeyoyin , Oluwakayode Bamiduro, Horace Whitworth. Extension of a Probabilistic Mesomechanics Based Model forFatigue Notch Factor to Titanium Alloy Components, Procedia materials science, (06 2014): 1860. doi:
TOTAL:	**1**

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Number of Presentations: 2.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received	Paper
TOTAL:	

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received		Paper
06/19/2012	1.00	Gbadebo Owolabi, Horace Whitworth. A NEW EXTREME-VALUE PROBABILISTIC FRAMEWORK FOR PREDCITING FATIGUE CRACK INITIATION LIFE OF NOTCHED COMPONENTS, Proceedings of the ASME 2011 International Mechanical Engineering Congress & ExpositionIMECE2011November 11-17, 2011, Denver, Colorado, USA . 11-NOV-11, . : ,
06/19/2012	4.00	Gbadebo Owolabi, Li Shi, Benedict Egboiyi. THE INFLUENCE OF INCLUSIONS ON MICROSTRUCTURALLY SMALL CRACK FORMATION AND GROWTH FROM NOTCH ROOT, Proceedings of the ASME 2012 Mechanical Engineering Congress and Exposition IMECE2012, November 9-15, 2012, Houston, TX, USA . 09-NOV-12, . : ,
06/19/2012	3.00	Benedict Egboiyi, Horace Whitworth, Olanrewaju Aluko, Gbadebo Owolabi. ON FATIGUE STRENGTH REDUCTION FACTOR: STATE OF THE ART, Proceedings of the ASME 2012 International Mechanical Engineering Congress &Exposition IMECE2012 November 9-15, 2012, Houston, Texas, USA. 09-NOV-12, . : ,

TOTAL: **3**

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received		Paper
06/19/2012	2.00	Horace Whitworth, Gbadeb Owolabi, Benedict Egboiyi, Li Shi. Microstructure-Dependent Fatigue Damage Process Zone and Notch Sensitivity Index, International Journal of Fracture (01 2011)
09/12/2013	8.00	Oluwamayowa Okeyoyin, Gbadebo Moses Owolabi. Application of Weakest Link Probabilistic Framework for Fatigue Notch Factor to Turbine Engine Materials , World journal of mechanics (05 2013)

TOTAL: **2**

Number of Manuscripts:

Books

Received Book

TOTAL:

Received Book Chapter

TOTAL:

Patents Submitted

Patents Awarded

Awards

- George David/ United Technology Corporation Assistant Professor (2012-Date)
- Tau Beta Pi Engineering Honor Society, April 2014.
- Chaired "Fatigue Failure in Engineering Materials and Structures" for the ASME International Mechanical Engineering Congress and Exposition, IMECE-2012-IMECE- 2013.

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Oluwamayowa Okeyoyin	1.00	
Li Shi	1.00	
Benedict Egboiyi	1.00	
FTE Equivalent:	**3.00**	
Total Number:	**3**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Gbadebo Moses Owolabi	1.00	
FTE Equivalent:	**1.00**	
Total Number:	**1**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED	Discipline
Victoria Adejumo	0.30	Chemical Engineering
Alexanderia Poole	0.00	Mechanical Engineering
Liu Jones	0.00	Mechanical Engineering
Kahsta Rennie	0.00	Mechanical Engineering
Alex Peterson	0.30	Mechanical Engineering
FTE Equivalent:	**0.60**	
Total Number:	**5**	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 5.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 5.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 2.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 2.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 2.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:...... 1.00

Names of Personnel receiving masters degrees

NAME	
Oluwamayowa Okeyoyin	
Li Shi	
Benedict Egboiyi	
Total Number:	**3**

Names of personnel receiving PHDs

NAME

Total Number:

Names of other research staff

NAME	PERCENT_SUPPORTED
Mathew Osagie	0.10
Kieron Bradshaw	0.30
Lekan Adewuyi	0.10
Ravi Jaglah	0.20
Atiba Brereton	0.10
Adewale Olasumboye	0.30
Odoh Daniel	0.50
FTE Equivalent:	**1.60**
Total Number:	**7**

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

Abstract:
This research, funded by the Department of Defense via the Research and Education Program for Historically Black Colleges and Universities and Minority-Serving Institutions (HBCU/MI), was conducted at the Applied Mechanics and Materials Research Laboratory, Howard University, Washington, DC from May 1, 2011 through October 31, 2014. The overall objective of the project is to develop and implement robust simulation-based strategies for notch root analysis and fatigue life prediction that account for the interactions between the complexity of the material microstructures and the notch-root stress gradients. A new probabilistic framework was developed to analyze the fatigue potency of notched specimens in order to improve the prediction of high cycle fatigue (HCF) of notched components. Multiscale modeling of microstructure was also conducted on oxygen free high conductivity copper (OFHC Cu) to identify important microstructural features and to develop mathematically consistent and physically meaningful methods to incorporate the effects of these features on the localized plastic deformation and the fatigue performance at both microstructure and geometric notch root scales. The simulation results show that the local driving force for fatigue crack nucleation can vary significantly between different microstructures. This approach can be used with limited experiments to help validate new materials or manufacturing technique to create a variant form of an existing material. The probabilistic framework based on Weibull's weakest link and extreme-value statistics was subsequently extended to aero-engine materials including titanium alloy and nickel-base super alloys using simulation strategies that capture both the essence of notch root stress gradient and the complexity of realistic microstructures. Notch size effects and notch root inelastic behavior are combined with probability distributions of microscope stress-strain gradient and small crack initiation to inform minimum life design methods. A new approach which can be applied using crystal plasticity finite element or closed-form solution was also developed as a more robust approach for determining the fatigue notch factor than the existing classical methods.

2. Technical Accomplishment for Period Beginning May 1, 2011 to October 31, 2015

The following research tasks were conducted throughout the duration of the project.

Task 1: Framework for Microstructure-Dependent Fatigue Notch Factor

Objective: The objective of this task is to develop a new probabilistic framework to predict the fatigue notch factor and the probability of forming and growing small cracks from the notch root taking into consideration the material microstructure.

Approach: The strategy of this task is to use computational micromechanics to support the development of microstructure-sensitive methods for notch size effects by computing frequency distribution and spatial correlations of the stress and strain gradients around the notch root region for as a function of notch (See Fig 1 in the attachment section). More specifically,

- We performed microstructure sensitive crystal plasticity simulations of notch root response to assess the degree of heterogeneity of cyclic plastic deformation as a function of notch size for various realization of grains at the notch root for OFHC Cu (Fig. 1),
- We obtained statistical information regarding the distributions of stress and plastic strain gradients within a well-defined damage process zone that provided useful insight into the dependence of the fatigue notch factor and the probabilities of fatigue crack formation and early growth at the notch on the heterogeneity inherent in the actual microstructures,
- We developed a new microstructure-dependent fatigue notch factor and associated sensitivity index using simulations results within a well-defined damage process zone around the notch root region, and
- We established a new criterion for determining the volume of the fatigue damage process zone using a micromechanics-based approach.

The flow chart for this procedure is shown in Fig. 2.

Publication #1: Gbadebo Owolabi, Benedict Egboiyi, Li Shi and Horace Whitworth (2011). Microstructure-Dependent Fatigue Damage Process Zone and Notch Sensitivity Index. International Journal of Fracture; 170(2): 159-173.

Abstract: The development of simulation methods for calculating notch root parameters for purposes of estimating the fatigue life of notched components is a critical aspect of designing against fatigue failures. At present, however, treatment of the notch root stress and plastic strain field gradients, coupled with intrinsic length scales of grains or other material attributes, has yet to be developed. Ultimately, this approach will be necessary to form a predictive basis for notch size effects in forming and propagating microstructurally small cracks in real structural materials and components. In this study, computational micromechanics is used to clarify and distinguish process zone for crack formation and microstructurally small crack growth, relative to scale of notch root radius and spatial extent of stress concentration at the notch. A new nonlocal criterion for the fatigue damage process zone based on the distribution of a shear-based fatigue indicator parameter is proposed and used along with a statistical method to obtain a new microstructure-sensitive fatigue notch factor and associated notch sensitivity index, thereby extending notch sensitivity to explicitly incorporate microstructure sensitivity and attendant size effects via probabilistic arguments. The notch sensitivity values obtained for a range of notch root radii using the new statistical approach presented in this study predict the general trends obtained from experimental results available in literature.

Summary of Results: This work combines elements of crystal plasticity with new probabilistic methods for notch sensitivity based on computed slip distributions in the microstructure at the notch root. Our simulation results show that the local driving force for fatigue crack nucleation can vary significantly between different microstructures (Fig. 1). Simulation results obtained also show that higher notch root radius produces high probability for crack nucleation (Fig. 3). Statistical information regarding the distribution of the extreme-value of a shear based fatigue indicator parameter was also obtained and used in the development of a microstructure-dependent fatigue notch factor and associated notch sensitivity as a function of the heterogeneity inherent in the actual microstructures. The results indicate that the fatigue notch factor depends not only on the notch root radius but also strongly on the materials microstructures (Fig. 4). Therefore the probabilistic approach used in this study provides useful insight into the dependence of fatigue notch factor and associated notch sensitivity index on the heterogeneity inherent in the actual microstructures. This approach can be used in conjunction with limited experiments to help validate a new material or manufacturing technique to create a variant form of an existing material.

The probabilistic model presented adequately predicts the trends observed in the experimental results for the average values of the notch sensitivity index as a function of notch root radius (See Fig. 5). Since this formulation uses the extreme-value distribution within the fatigue damage process zone, it thus considers the effect of strain/stress gradient and is suitable for any simple or arbitrary geometries. It is computable for a given microstructure, and its predictive capabilities can be further assessed by validation with experiments other materials with different microstructures and the same notches, but care must be taken in using the appropriate crystal plasticity models and also defining the crack formation event(s) to avoid exercising the model beyond its limits. In addition to giving a better prediction of notch sensitivities for higher notch root radius when compared with the traditional Neuber's model (Fig. 5), this approach has certain advantages relative to the traditional approach since it can account for the variation in the microstructure of a given material and can also be used for qualitative comparison of notch sensitivities of various notch geometries for a range of microstructures of current materials and also for design projections for future materials that have yet been processed.

Publication #2: G.M. Owolabi and H.A. Whitworth (2013), On the Concept of Fatigue Notch factor. JP Journal of Solids and Structures; 6 (2-3): 63-88.

Abstract: Numerous theoretical models have been developed to predict the fatigue notch factor (also known as the fatigue strength reduction factor); an important parameter in the fatigue life prediction of notched components. These models include: the classical average stress method, the fracture mechanics (FM) method, the stress field intensity (SIF) method, the strain energy method, and the weakest link method. This paper gives a detailed literature review of these methods. It also discusses a recently developed probabilistic method for microstructure-sensitive fatigue notch factor. The probabilistic method provides a very strong physical basis for fatigue strength reduction and associated notch sensitivity; thus it can be used to determine the effect of notches on reduction of fatigue resistance in a way that directly incorporates microstructure. The results obtained using the new probabilistic framework and other conventional methods are compared with experimental data for notched components.

Summary of Results: The result shows that the fatigue notch factor at microscale level varies with microstructure for a given notch root radius. Therefore, this approach used in this work provides a clear picture of the dependence of fatigue notch factor and associated notch sensitivity index on the heterogeneity inherent in the actual microstructure. The results obtained from comparing the probabilistic framework with the conventional Neuber, Peterson, stress field intensity, and fracture mechanics models also show that the formulated probabilistic framework can predict fatigue life of notch component better than the conventional approaches for most of the notch root radii considered (Fig. 6).

Thesis Produced from the Task: Benedict Egboiyi: (MS Thesis-Completed, May 2012): Extreme-Value Probabilistic Method for Estimating Microstructure-Dependent Fatigue Notch Factor

Task 2: Extension of Probabilistic Framework for Notch Analysis to Multiphase Materials and Development of Simplified Close-Form Solution Method

Objective: The objective of this task is to extend the new probabilistic framework, which has been implemented for a single-phase OFHC Cu material to multiphase materials such as titanium alloy nickel-base superalloy in order to improve the prediction of HCF of notched turbine engine components such as the blades and disks employing these materials with complex microstructures. The concept of fatigue strength reduction factor, Kf, typically defined as the ratio of unnotched to notched specimen fatigue strength in the HCF regime was extended to these materials to incorporate microstructure sensitivity using probabilistic arguments for these materials.

Approach: The notched geometry modeled in this work is a v-notched cylindrical component schematically represented as shown in Fig. 7. Different test cases are modeled which include: (a) nickel base superalloy specimen without inclusion (b) nickel base superalloy specimen with horizontal elliptical inclusion at varied distance from the notch root (c) nickel base specimen superalloy with inclusions at various orientations, and (d) titanium alloy specimens with different notch root radius and acuity. Results of these thrusts were integrated in this task to form the basis of a quantitative scheme for estimating the gradient fields

around notches and corresponding fatigue strength reduction factor of for safety critical components as well as the probability of formation of small cracks in safety-critical components. For practical engineering application, a more simplified and approximate model for fatigue notch factor was developed based on closed form solution for stress distribution at the notch developed by Glinka using the Creager-Paris solutions of the stress field ahead of a crack.

Publication # 1: Okeyoyin, O.A., Owolabi, G.M. (2013). Application of Weakest Link Probabilistic Framework for Fatigue Notch Factor to Turbine Engine Materials. World Journal of Mechanics; 3: 237-244.

Abstract: This paper is concerned with the extension of a recently developed probabilistic framework based on Weibull's weakest link and extreme-value statistics to aero-engine materials like titanium alloy and nickel-base super alloys using simulation strategies that capture both the essence of notch root stress gradient and the complexity of realistic microstructures. In this paper, notch size effects and notch root inelastic behavior are combined with probability distributions of microscale stress-strain gradient and small crack initiation to inform minimum life design methods. A new approach which can be applied using crystal plasticity finite element or closed-form solution is also proposed as a more robust approach for determining fatigue notch factor than the existing classical methods. The fatigue notch factors predicted using the new framework are in good agreements with experimental results obtained from literature for notched titanium alloy specimens subjected to uniaxial cyclic loads with various stress ratio.

Summary of Results: The stress distribution obtained from the numerical simulations used to determine the average fatigue notch factor, Kf for the geometry using the probabilistic framework based on Weibull's weakest link and extreme-value statistics. Also as a further validation of the approach, the value of Kf was calculated using a closed form solution for fatigue notch factor developed as part of this study. The results obtained are compared to experimental results shown in Table 1. Both results are in agreement with the experimental results with minimal difference. Also, the radius of curvature at the notch root plays a vital role on the stress gradient at the notch. This effect is captured by the fatigue notch sensitivity factor. Figure 8 gives a plot of the notch sensitivity factor as a function of the notch root radius for the different load ratio. The straight line plot represents the notch sensitivity factor calculated using the Neuber's formulation with a material constant of 0.2 for titanium alloy Ti-6Al-4V. The plot shows that the new approach and the closed-form solutions give more accurate result compared to the existing Neuber's formulation.

Publication # 2: Gbadebo Owolabi, Oluwamayowa Okeyoyin, Oluwakayode Bamiduro, Horace Whitworth (2014). Fatigue Strength Reduction Factor for Polycrystalline Nickel Base Superalloy with and without Non-Metallic Inclusion; Procedia Engineering; 74: 297-302.

Abstract: Polycrystalline nickel base superalloy is popular for its wide applications; it is used in hot sections of power generation turbines, rocket engines and other challenging conditions due to its high strength and good creep, fatigue, and corrosion resistance at high temperature. However, the presence of inclusions introduced into the superalloy during the fabrication processes can significantly degrade the fatigue life. This paper utilizes a new probabilistic method which captures both the essence of microstructure and notch root stress gradient to determine the notch size and inclusions effects on the fatigue strength of notched nickel base superalloy with and without non-metallic inclusions. Notched cylindrical specimens of nickel base superalloy of varying notch root radii are modeled using microstructural-sensitive crystal plasticity finite element codes. The stresses extracted from the fatigue damage process zone around the notch are used in determining the fatigue strength reduction factor and the associated probability of failure of the notched specimens. The numerical results obtained are in direct correlation with the experimentally obtained value for the different notch root radii.

Summary of Results: The result shows that the grain orientation and the presence of inclusions play an important role in predicting the fatigue strength of the material. A significant change is noted in the maximum stress of the notched nickel base superalloy when the orientation of the inclusion is changed from horizontal to vertical. The changes is also reflected in the associated fatigue notch factor with horizontal orientation of inclusion having the lowest fatigue notch factor of 2.01 and the diagonal orientation of grain having the highest fatigue notch factor of 2.38. It can be inferred from this observation that vertical and inclined inclusion are more detrimental to fatigue failure and effort should be made to avoid them in metal forming operations of nickel based superalloy. Figure 9 shows that the introduction of one horizontal inclusion in the matrix of the notched nickel base superalloy increases the fatigue notch factor. Thus component with inclusions of any kind will tend to have lower fatigue strength than components without inclusion. This is expected based on the fact that inclusions serve as favorable sites of premature plastic deformation due to high stress concentration in the vicinity of the inclusion curvature.
Thesis Produced from the Task: Mayowa Okeyoyin: (MS Thesis-Completed, December 2013): Probabilistic Mesomechanics-Based Methods for Fatigue Life Prediction of Turbine Engine Materials

Task 3: Modeling Microstructurally Small Crack Growth in Nickel-base superalloy

Objective: The objective of this task is to develop a probabilistic framework for predicting HCF life of microstructurally small crack formation and growth in notched polycrystalline nickel-base superalloys and to quantify the variability in the driving force for formation and growth of microstructurally small crack from notch root in the matrix with non-metallic inclusions.

Publication # 1a: Gbadebo Owolabi and Horace Whitworth (2014). Modeling and Simulation of Microstructurally Small Crack Formation and Growth in Notched Nickel-base Superalloy Component. Journal of Materials Science and Technology; 30 (3): 203-212.

Publication 1b: L. Shi, G.M. Owolabi and R. Prasannavenkatesan (2012), Microstructurally Small Crack Formation and Growth in Notched Component with Non-Metallic Inclusions. Proceedings of The Canadian Society for Mechanical Engineering International Congress 2012 CSME International Congress 2012 June 4-6, 2012, Winnipeg, Manitoba, Canada, 7 pages.

Abstract: Studies on microstructurally small fatigue cracks have illustrated that heterogeneous microstructural features such as inclusions, pores, grain size distribution as well as precipitate size distribution and volume fraction create stochasticity in their behavior under cyclic loads. Therefore, to enhance safe-life and damage-tolerance approaches, accurate modeling of the influence of these heterogeneous microstructural features on microstructural small crack formation and growth from stress raisers is necessary. In this work, computational micromechanics is used to predict the high cycle fatigue of microstructurally small crack formation and growth in notched polycrystalline nickel-base superalloys and to quantify the variability in the driving force for formation and growth of microstructurally small crack from notch root in the matrix with non-metallic inclusions. The framework involves computational modeling to obtain three dimensional perspectives of microstructural features influencing fatigue crack growth in notched nickel-base superaloys, which accounts for the effects of nonlocal notch root plasticity, loading microstructural variability, and extrinsic defects on local cyclic plasticity at the microstructure-scale level. This approach can be used to explore sensitivity of minimum fatigue lifetime to microstructures. The simulation results obtained from this framework are calibrated to existing experimental results for polycrystalline nickel-base superalloys.

Summary of Results: The computational framework was used to determine the influence of non-metallic inclusions and notches on the formation and growth of microstructurally small crack in polycrystalline IN 100 superalloy and to assess the effects of the non-metallic inclusions on the fatigue life and the probability of fatigue failure of notched polycrystalline IN 100 components. The distribution of the effective plastic strains around the notch and the inclusions is used to estimate the driving forces for crack formation and microstructurally small crack growth in the notched IN 100 with non-metallic inclusions. The finite element simulation results show that the driving force for notched component with inclusions is higher than the notched component without inclusions. The results also show that the larger the notch radius, the higher the probability of formation and growth of microstructurally small crack. Comparison between fatigue lives for notched component with inclusions and experimental results for smooth component shows that the presence of notch and inclusions leads to a drastic drop in the fatigue life.

Thesis Produced from the Task: Li Shi: (MS Thesis-Completed, May 2012): Microstructurally Small Crack Growth Modeling in Notched Components with Non-Metallic Inclusions

1. Dissemination

The outcomes of this completed project have been published in 7 international journals [1-7] and 7 conference proceedings [8-14] (see the reference below). We have also presented the work in 7 international conference i) The Canadian Society for Mechanical Engineering International Congress 2012 CSME International Congress 2012 June 4-6, 2012, Winnipeg, Manitoba, Canada in which the PI is the organizer and chair of the Symposium on Recent Developments in Fatigue and Fracture of Engineering Materials and Structures, ii) 13th International Conference on Fracture, Beijing China, June 16-21, 2013, iii) XVII International Colloquium "Mechanical Fatigue of Metal, Verbania, Italy, June 25-27, 2014, iv) the 20th European Conference on Fracture, 30th of June-4th of July, Trondheim, Norway, v) ASME International Mechanical Engineering Congress and Exposition, IMECE-2011, November 11-17, 2011, Denver, Colorado, USA. vi) ASME International Mechanical Engineering Congress and Exposition, IMECE-2012, November 9-15, 2013, Houston, Texas, USA. vii) ASME International Mechanical Engineering Congress and Exposition, IMECE-2013, November 15-21, 2013, San-Diego, California, USA. 3 graduate theses completed their graduate degrees, 5 undergraduate students and several graduate students have also participated in the project.

3. Relevance to DOD

Fatigue is a critical issue in reliability analysis of numerous components and structure used in the military and other large industrial applications such as automotive and aerospace. The probabilistic framework developed in this work will assist in the design of structural components for low probabilities of failure in high cycle fatigue and can also potentially be used to support design projections for microstructures that have not yet been processed or tested. A better understanding of probability of formation and growth of small crack will allow for less conservative maintenance schedules. This will facilitate better life predictions for existing components and more efficient new component designs for many applications that couple microstructure with component level analysis.

4. Collaborations and Technology Transfer

- Ed Habtour, Mechanical Engineer, U.S. Army Research Laboratory Vehicle Technology Directorate, RDRL-VTV, Technology Development and Transition Team)
- Dr. Jaret C. Riddick, Lead Structural Integrity and Durability Team, U.S. Army Research Laboratory, Vehicle Technology

Directorate) at the ARL, Aberdeen Proving Ground.
• This project complements the ongoing research in AFRL. The results of this completed project will be transferred to both the AFRL and ARL.

5. Resulting Journal Publications

Peer-Reviewed Journal Papers

1. G.M. Owolabi and H.A. Whitworth (2014). Modeling and Simulation of Microstructurally Small Crack Formation and Growth in Notched Nickel-base Superalloy Component. Journal of Materials Science and Technology; 30 (3): 203-212.
2. Gbadebo Owolabi, Oluwamayowa Okeyoyin, Oluwakayode Bamiduro, Horace Whitworth (2014). Extension of a Probabilistic Mesomechanics Based Model for Fatigue Notch Factor to Titanium Alloy Components. Procedia Materials Science; 3: 1860-1865.
3. Gbadebo Owolabi, Oluwamayowa Okeyoyin, Oluwakayode Bamiduro, Horace Whitworth (2014). Fatigue Strength Reduction Factor for Polycrystalline Nickel Base Superalloy with and without Non-Metallic Inclusion; Procedia Engineering; 74: 297-302.
4. Okeyoyin, O.A., Owolabi, G.M. (2013). Application of Weakest Link Probabilistic Framework for Fatigue Notch Factor to Turbine Engine Materials. World Journal of Mechanics; 3: 237-244.
5. G.M. Owolabi and H.A. Whitworth (2013). Microstructually Small Crack Formation and Growth in Notched Turbine Engine Materials. JP Journal of Solid and Structures; 7(1): 1-26.
6. G.M. Owolabi and H.A. Whitworth (2013), On the Concept of Fatigue Notch Factor. JP Journal of Solids and Structures; 6 (2-3): 63-88.
7. Gbadebo Owolabi, Benedict Egboiyi, Li Shi and Horace Whitworth (2011). Microstructure-Dependent Fatigue Damage Process Zone and Notch Sensitivity Index. International Journal of Fracture; 170(2): 159-173.

Conference Presentations and Proceedings

8. G.M.Owolabi and H.A. Whitworth (2011). A New Extreme-Value Probabilistic Framework for Predicting Fatigue Crack Initiation Life of Notched Components. Proceedings of the ASME International Mechanical Engineering Congress and Exposition, IMECE-2011, November 11-17, 2011, Denver, Colorado, USA: 10 pages.
9. G.M. Owolabi, B. Egboiyi, H.A. Whitworth and O. Aluko (2012). On Fatigue Strength Reduction Factor, State-of-the-Art, Proceedings of the ASME International Mechanical Engineering Congress and Exposition, IMECE-2012, November 5-11, 2012, Houston, Texas, USA: 10 pages.
10. L. Shi, G.M. Owolabi and R. Prasannavenkatesan (2012), Microstructurally Small Crack Formation and Growth in Notched Component with Non-Metallic Inclusions. Proceedings of The Canadian Society for Mechanical Engineering International Congress 2012 CSME International Congress 2012 June 4-6, 2012, Winnipeg, Manitoba, Canada, 7 pages.
11. Okeyoyin, O.A., Owolabi, G.M. (2013), Effects of Nonmetallic Inclusions on the Fatigue Notch Factor of Polycrystalline Nickel-base Superalloy. Proceedings of the 2013 International Mechanical Engineering Congress and Exposition, Nov. 15-21, 2013, San Diego, CA, USA. Paper #: IMECE2013-63230.
12. Okeyoyin, O.A., Owolabi, G.M. (2013). Application of Weakest Link Probabilistic Framework for Fatigue Notch Factor to Turbine Engine Materials. 13th International Conference on Fracture, Beijing China, June 16-21, 2013.
13. Gbadebo Owolabi, Oluwamayowa Okeyoyin, Oluwakayode Bamiduro, Horace Whitworth (2014). Extension of a Probabilistic Mesomechanics Based Model for Fatigue Notch Factor to Titanium Alloy Components. The 20th European Conference on Fracture, 30th of June-4th of July, Trondheim, Norway.
14. Gbadebo Owolabi, Oluwamayowa Okeyoyin, Oluwakayode Bamiduro, Horace Whitworth (2014), Fatigue Strength Reduction Factor for Polycrystalline Nickel Base Superalloy with and without Non-Metallic Inclusion. XVII International Colloquium "Mechanical Fatigue of Metal, Verbania, Italy, June 25-27, 2014.

Technology Transfer

• Ed Habtour, Mechanical Engineer, U.S. Army Research Laboratory Vehicle Technology Directorate, RDRL-VTV, Technology Development and Transition Team)
• Dr. Jaret C. Riddick, Lead Structural Integrity and Durability Team, U.S. Army Research Laboratory, Vehicle Technology Directorate) at the ARL, Aberdeen Proving Ground.
• This project complements the ongoing research in AFRL. The results of this completed project will be transferred to both the AFRL and ARL

FINAL REPORT

Funded Project: Microstructure-Sensitive Fatigue Design of Notched Components
Proposal #: 58941-RT-REP
Grant Award #: W911NF-11-1-041
Reporting Period: May 01, 2011-October 31, 2014
Principal Investigator: G.M. Owolabi, Howard University, Washington D.C.

Abstract:

This research, funded by the Department of Defense via the Research and Education Program for Historically Black Colleges and Universities and Minority-Serving Institutions (HBCU/MI), was conducted at the Applied Mechanics and Materials Research Laboratory, Howard University, Washington, DC from May 1, 2011 through October 31, 2014. The overall objective of the project is to develop and implement robust simulation-based strategies for notch root analysis and fatigue life prediction that account for the interactions between the complexity of the material microstructures and the notch-root stress gradients. A new probabilistic framework was developed to analyze the fatigue potency of notched specimens in order to improve the prediction of high cycle fatigue (HCF) of notched components. Multiscale modeling of microstructure was also conducted on oxygen free high conductivity copper (OFHC Cu) to identify important microstructural features and to develop mathematically consistent and physically meaningful methods to incorporate the effects of these features on the localized plastic deformation and the fatigue performance at both microstructure and geometric notch root scales. The simulation results show that the local driving force for fatigue crack nucleation can vary significantly between different microstructures. This approach can be used with limited experiments to help validate new materials or manufacturing technique to create a variant form of an existing material. The probabilistic framework based on Weibull's weakest link and extreme-value statistics was subsequently extended to aero-engine materials including titanium alloy and nickel-base super alloys using simulation strategies that capture both the essence of notch root stress gradient and the complexity of realistic microstructures. Notch size effects and notch root inelastic behavior are combined with probability distributions of microscope stress-strain gradient and small crack initiation to inform minimum life design methods. A new approach which can be applied using crystal plasticity finite element or closed-form solution was also developed as a more robust approach for determining the fatigue notch factor than the existing classical methods.

2. Technical Accomplishment for Period Beginning May 1, 2011 to October 31, 2015

The following research tasks were conducted throughout the duration of the project.

Task 1: Framework for Microstructure-Dependent Fatigue Notch Factor

Objective: The objective of this task is to develop a new probabilistic framework to predict the fatigue notch factor and the probability of forming and growing small cracks from the notch root taking into consideration the material microstructure.

Approach: The strategy of this task is to use computational micromechanics to support the development of microstructure-sensitive methods for notch size effects by computing frequency distribution and spatial correlations of the stress and strain gradients around the notch root region for as a function of notch (See Fig 1 in the attachment section). More specifically,

- We performed microstructure sensitive crystal plasticity simulations of notch root response to assess the degree of heterogeneity of cyclic plastic deformation as a function of notch size for various realization of grains at the notch root for OFHC Cu (Fig. 1),
- We obtained statistical information regarding the distributions of stress and plastic strain gradients within a well-defined damage process zone that provided useful insight into the dependence of the fatigue notch factor and the probabilities of fatigue crack formation and early growth at the notch on the heterogeneity inherent in the actual microstructures,
- We developed a new microstructure-dependent fatigue notch factor and associated sensitivity index using simulations results within a well-defined damage process zone around the notch root region, and
- We established a new criterion for determining the volume of the fatigue damage process zone using a micromechanics-based approach.

The flow chart for this procedure is shown in Fig. 2.

Publication #1: Gbadebo Owolabi, Benedict Egboiyi, Li Shi and Horace Whitworth (2011). *Microstructure-Dependent Fatigue Damage Process Zone and Notch Sensitivity Index.* International Journal of Fracture; 170(2): 159-173.

Abstract: The development of simulation methods for calculating notch root parameters for purposes of estimating the fatigue life of notched components is a critical aspect of designing against fatigue failures. At present, however, treatment of the notch root stress and plastic strain field gradients, coupled with intrinsic length scales of grains or other material attributes, has yet to be developed. Ultimately, this approach will be necessary to form a predictive basis for notch size effects in forming and propagating microstructurally small cracks in real structural materials and components. In this study, computational micromechanics is used to clarify and distinguish process zone for crack formation and microstructurally small crack growth, relative to scale of notch root radius and spatial extent of stress concentration at the notch. A new nonlocal criterion for the fatigue damage process zone based on the distribution of a shear-based fatigue indicator parameter is proposed and used along with a statistical method to obtain a new microstructure-sensitive fatigue notch factor and associated notch sensitivity index, thereby extending notch sensitivity to explicitly incorporate microstructure sensitivity and attendant size effects via probabilistic arguments. The notch sensitivity values obtained for a range of notch root radii using the new statistical approach presented in this study predict the general trends obtained from experimental results available in literature.

Summary of Results: This work combines elements of crystal plasticity with new probabilistic methods for notch sensitivity based on computed slip distributions in the microstructure at the notch root. Our simulation results show that the local driving force for fatigue crack nucleation can vary significantly between different microstructures (Fig. 1). Simulation results obtained also show that higher notch root radius produces high probability for crack nucleation (Fig. 3).

Statistical information regarding the distribution of the extreme-value of a shear based fatigue indicator parameter was also obtained and used in the development of a microstructure-dependent fatigue notch factor and associated notch sensitivity as a function of the heterogeneity inherent in the actual microstructures. The results indicate that the fatigue notch factor depends not only on the notch root radius but also strongly on the materials microstructures (Fig. 4). Therefore the probabilistic approach used in this study provides useful insight into the dependence of fatigue notch factor and associated notch sensitivity index on the heterogeneity inherent in the actual microstructures. This approach can be used in conjunction with limited experiments to help validate a new material or manufacturing technique to create a variant form of an existing material.

The probabilistic model presented adequately predicts the trends observed in the experimental results for the average values of the notch sensitivity index as a function of notch root radius (See Fig. 5). Since this formulation uses the extreme-value distribution within the fatigue damage process zone, it thus considers the effect of strain/stress gradient and is suitable for any simple or arbitrary geometries. It is computable for a given microstructure, and its predictive capabilities can be further assessed by validation with experiments other materials with different microstructures and the same notches, but care must be taken in using the appropriate crystal plasticity models and also defining the crack formation event(s) to avoid exercising the model beyond its limits. In addition to giving a better prediction of notch sensitivities for higher notch root radius when compared with the traditional Neuber's model (Fig. 5), this approach has certain advantages relative to the traditional approach since it can account for the variation in the microstructure of a given material and can also be used for qualitative comparison of notch sensitivities of various notch geometries for a range of microstructures of current materials and also for design projections for future materials that have yet been processed.

Publication #2: G.M. Owolabi and H.A. Whitworth (2013), *On the Concept of Fatigue Notch factor*. JP Journal of Solids and Structures; 6 (2-3): 63-88.

Abstract: Numerous theoretical models have been developed to predict the fatigue notch factor (also known as the fatigue strength reduction factor); an important parameter in the fatigue life prediction of notched components. These models include: the classical average stress method, the fracture mechanics (FM) method, the stress field intensity (SIF) method, the strain energy method, and the weakest link method. This paper gives a detailed literature review of these methods. It also discusses a recently developed probabilistic method for microstructure-sensitive fatigue notch factor. The probabilistic method provides a very strong physical basis for fatigue strength reduction and associated notch sensitivity; thus it can be used to determine the effect of notches on reduction of fatigue resistance in a way that directly incorporates microstructure. The results obtained using the new probabilistic framework and other conventional methods are compared with experimental data for notched components.

Summary of Results: The result shows that the fatigue notch factor at microscale level varies with microstructure for a given notch root radius. Therefore, this approach used in this work provides a clear picture of the dependence of fatigue notch factor and associated notch sensitivity index on the heterogeneity inherent in the actual microstructure. The results obtained from comparing the probabilistic framework with the conventional Neuber, Peterson, stress field intensity, and fracture mechanics models also show that the formulated probabilistic framework can predict fatigue life

of notch component better than the conventional approaches for most of the notch root radii considered (Fig. 6).

Thesis Produced from the Task: Benedict Egboiyi: (MS Thesis-Completed, May 2012): Extreme-Value Probabilistic Method for Estimating Microstructure-Dependent Fatigue Notch Factor

Task 2: Extension of Probabilistic Framework for Notch Analysis to Multiphase Materials and Development of Simplified Close-Form Solution Method

Objective: The objective of this task is to extend the new probabilistic framework, which has been implemented for a single-phase OFHC Cu material to multiphase materials such as titanium alloy nickel-base superalloy in order to improve the prediction of HCF of notched turbine engine components such as the blades and disks employing these materials with complex microstructures. The concept of fatigue strength reduction factor, K_f, typically defined as the ratio of unnotched to notched specimen fatigue strength in the HCF regime was extended to these materials to incorporate microstructure sensitivity using probabilistic arguments for these materials.

Approach: The notched geometry modeled in this work is a v-notched cylindrical component schematically represented as shown in Fig. 7. Different test cases are modeled which include: (a) nickel base superalloy specimen without inclusion (b) nickel base superalloy specimen with horizontal elliptical inclusion at varied distance from the notch root (c) nickel base specimen superalloy with inclusions at various orientations, and (d) titanium alloy specimens with different notch root radius and acuity. Results of these thrusts were integrated in this task to form the basis of a quantitative scheme for estimating the gradient fields around notches and corresponding fatigue strength reduction factor of for safety critical components as well as the probability of formation of small cracks in safety-critical components. For practical engineering application, a more simplified and approximate model for fatigue notch factor was developed based on closed form solution for stress distribution at the notch developed by Glinka using the Creager-Paris solutions of the stress field ahead of a crack.

Publication # 1: Okeyoyin, O.A., Owolabi, G.M. (2013). *Application of Weakest Link Probabilistic Framework for Fatigue Notch Factor to Turbine Engine Materials*. World Journal of Mechanics; 3: 237-244.

Abstract: This paper is concerned with the extension of a recently developed probabilistic framework based on Weibull's weakest link and extreme-value statistics to aero-engine materials like titanium alloy and nickel-base super alloys using simulation strategies that capture both the essence of notch root stress gradient and the complexity of realistic microstructures. In this paper, notch size effects and notch root inelastic behavior are combined with probability distributions of microscale stress-strain gradient and small crack initiation to inform minimum life design methods. A new approach which can be applied using crystal plasticity finite element or closed-form solution is also proposed as a more robust approach for determining fatigue notch factor than the existing classical methods. The fatigue notch factors predicted using the new framework are in good agreements with experimental results obtained from literature for notched titanium alloy specimens subjected to uniaxial cyclic loads with various stress ratio.

Summary of Results: The stress distribution obtained from the numerical simulations used to determine the average fatigue notch factor, K_f for the geometry using the probabilistic framework based on Weibull's weakest link and extreme-value statistics. Also as a further validation of the approach, the value of K_f was calculated using a closed form solution for fatigue notch factor developed as part of this study. The results obtained are compared to experimental results shown in Table 1. Both results are in agreement with the experimental results with minimal difference. Also, the radius of curvature at the notch root plays a vital role on the stress gradient at the notch. This effect is captured by the fatigue notch sensitivity factor. Figure 8 gives a plot of the notch sensitivity factor as a function of the notch root radius for the different load ratio. The straight line plot represents the notch sensitivity factor calculated using the Neuber's formulation with a material constant of 0.2 for titanium alloy Ti-6Al-4V. The plot shows that the new approach and the closed-form solutions give more accurate result compared to the existing Neuber's formulation.

Publication # 2: Gbadebo Owolabi, Oluwamayowa Okeyoyin, Oluwakayode Bamiduro, Horace Whitworth (2014). *Fatigue Strength Reduction Factor for Polycrystalline Nickel Base Superalloy with and without Non-Metallic Inclusion*; Procedia Engineering; 74: 297-302.

Abstract: Polycrystalline nickel base superalloy is popular for its wide applications; it is used in hot sections of power generation turbines, rocket engines and other challenging conditions due to its high strength and good creep, fatigue, and corrosion resistance at high temperature. However, the presence of inclusions introduced into the superalloy during the fabrication processes can significantly degrade the fatigue life. This paper utilizes a new probabilistic method which captures both the essence of microstructure and notch root stress gradient to determine the notch size and inclusions effects on the fatigue strength of notched nickel base superalloy with and without non-metallic inclusions. Notched cylindrical specimens of nickel base superalloy of varying notch root radii are modeled using microstructural-sensitive crystal plasticity finite element codes. The stresses extracted from the fatigue damage process zone around the notch are used in determining the fatigue strength reduction factor and the associated probability of failure of the notched specimens. The numerical results obtained are in direct correlation with the experimentally obtained value for the different notch root radii.

Summary of Results: The result shows that the grain orientation and the presence of inclusions play an important role in predicting the fatigue strength of the material. A significant change is noted in the maximum stress of the notched nickel base superalloy when the orientation of the inclusion is changed from horizontal to vertical. The changes is also reflected in the associated fatigue notch factor with horizontal orientation of inclusion having the lowest fatigue notch factor of 2.01 and the diagonal orientation of grain having the highest fatigue notch factor of 2.38. It can be inferred from this observation that vertical and inclined inclusion are more detrimental to fatigue failure and effort should be made to avoid them in metal forming operations of nickel based superalloy. Figure 9 shows that the introduction of one horizontal inclusion in the matrix of the notched nickel base superalloy increases the fatigue notch factor. Thus component with inclusions of any kind will tend to have lower fatigue strength than components without inclusion. This is expected based on the fact that inclusions serve as favorable sites of premature plastic deformation due to high stress concentration in the vicinity of the inclusion curvature.

Thesis Produced from the Task: Mayowa Okeyoyin: (MS Thesis-Completed, December 2013): Probabilistic Mesomechanics-Based Methods for Fatigue Life Prediction of Turbine Engine Materials

Task 3: Modeling Microstructurally Small Crack Growth in Nickel-base superalloy

Objective: The objective of this task is to develop a probabilistic framework for predicting HCF life of microstructurally small crack formation and growth in notched polycrystalline nickel-base superalloys and to quantify the variability in the driving force for formation and growth of microstructurally small crack from notch root in the matrix with non-metallic inclusions.

Publication # 1a: Gbadebo Owolabi and Horace Whitworth (2014). *Modeling and Simulation of Microstructurally Small Crack Formation and Growth in Notched Nickel-base Superalloy Component*. Journal of Materials Science and Technology; 30 (3): 203-212.

Publication 1b: L. Shi, G.M. Owolabi and R. Prasannavenkatesan (2012), *Microstructurally Small Crack Formation and Growth in Notched Component with Non-Metallic Inclusions.* Proceedings of The Canadian Society for Mechanical Engineering International Congress 2012 CSME International Congress 2012 June 4-6, 2012, Winnipeg, Manitoba, Canada, 7 pages.

Abstract: Studies on microstructurally small fatigue cracks have illustrated that heterogeneous microstructural features such as inclusions, pores, grain size distribution as well as precipitate size distribution and volume fraction create stochasticity in their behavior under cyclic loads. Therefore, to enhance safe-life and damage-tolerance approaches, accurate modeling of the influence of these heterogeneous microstructural features on microstructural small crack formation and growth from stress raisers is necessary. In this work, computational micromechanics is used to predict the high cycle fatigue of microstructurally small crack formation and growth in notched polycrystalline nickel-base superalloys and to quantify the variability in the driving force for formation and growth of microstructurally small crack from notch root in the matrix with non-metallic inclusions. The framework involves computational modeling to obtain three dimensional perspectives of microstructural features influencing fatigue crack growth in notched nickel-base superaloys, which accounts for the effects of nonlocal notch root plasticity, loading microstructural variability, and extrinsic defects on local cyclic plasticity at the microstructure-scale level. This approach can be used to explore sensitivity of minimum fatigue lifetime to microstructures. The simulation results obtained from this framework are calibrated to existing experimental results for polycrystalline nickel-base superalloys.

Summary of Results: The computational framework was used to determine the influence of non-metallic inclusions and notches on the formation and growth of microstructurally small crack in polycrystalline IN 100 superalloy and to assess the effects of the non-metallic inclusions on the fatigue life and the probability of fatigue failure of notched polycrystalline IN 100 components. The distribution of the effective plastic strains around the notch and the inclusions is used to estimate the driving forces for crack formation and microstructurally small crack growth in the notched IN 100 with non-metallic inclusions. The finite element simulation results show that the driving force for notched component with inclusions is higher than the notched component without inclusions. The results also show that the larger the notch radius, the higher the probability of formation and growth of microstructurally small crack. Comparison between fatigue lives for

notched component with inclusions and experimental results for smooth component shows that the presence of notch and inclusions leads to a drastic drop in the fatigue life.

Thesis Produced from the Task: Li Shi: (MS Thesis-Completed, May 2012): Microstructurally Small Crack Growth Modeling in Notched Components with Non-Metallic Inclusions

1. *Dissemination*

The outcomes of this completed project have been published in 7 international journals [1-7] and 7 conference proceedings [8-14] (see the reference below). We have also presented the work in 7 international conference i) The Canadian Society for Mechanical Engineering International Congress 2012 CSME International Congress 2012 June 4-6, 2012, Winnipeg, Manitoba, Canada in which the PI is the organizer and chair of the Symposium on Recent Developments in Fatigue and Fracture of Engineering Materials and Structures, ii) 13th International Conference on Fracture, Beijing China, June 16-21, 2013, iii) XVII International Colloquium "Mechanical Fatigue of Metal, Verbania, Italy, June 25-27, 2014, iv) the 20th European Conference on Fracture, 30th of June-4th of July, Trondheim, Norway, v) ASME International Mechanical Engineering Congress and Exposition**,** IMECE-2011, November 11-17, 2011, Denver, Colorado, USA. vi) ASME International Mechanical Engineering Congress and Exposition**,** IMECE-2012, November 9-15, 2013, Houston, Texas, USA. vii) ASME International Mechanical Engineering Congress and Exposition**,** IMECE-2013, November 15-21, 2013, San-Diego, California, USA. 3 graduate theses completed their graduate degrees, 5 undergraduate students and several graduate students have also participated in the project.

3. Relevance to DOD

Fatigue is a critical issue in reliability analysis of numerous components and structure used in the military and other large industrial applications such as automotive and aerospace. The probabilistic framework developed in this work will assist in the design of structural components for low probabilities of failure in high cycle fatigue and can also potentially be used to support design projections for microstructures that have not yet been processed or tested. A better understanding of probability of formation and growth of small crack will allow for less conservative maintenance schedules. This will facilitate better life predictions for existing components and more efficient new component designs for many applications that couple microstructure with component level analysis.

4. Collaborations and Technology Transfer

- Ed Habtour, Mechanical Engineer, U.S. Army Research Laboratory Vehicle Technology Directorate, RDRL-VTV, Technology Development and Transition Team)
- Dr. Jaret C. Riddick, Lead Structural Integrity and Durability Team, U.S. Army Research Laboratory, Vehicle Technology Directorate) at the ARL, Aberdeen Proving Ground.
- This project complements the ongoing research in AFRL. The results of this completed project will be transferred to both the AFRL and ARL.

5. Resulting Journal Publications

Peer-Reviewed Journal Papers

1. G.M. Owolabi and H.A. Whitworth (2014). *Modeling and Simulation of Microstructurally Small Crack Formation and Growth in Notched Nickel-base Superalloy Component*. Journal of Materials Science and Technology; 30 (3): 203-212.
2. Gbadebo Owolabi, Oluwamayowa Okeyoyin, Oluwakayode Bamiduro, Horace Whitworth (2014). *Extension of a Probabilistic Mesomechanics Based Model for Fatigue Notch Factor to Titanium Alloy Components*. Procedia Materials Science; 3: 1860-1865.
3. Gbadebo Owolabi, Oluwamayowa Okeyoyin, Oluwakayode Bamiduro, Horace Whitworth (2014). *Fatigue Strength Reduction Factor for Polycrystalline Nickel Base Superalloy with and without Non-Metallic Inclusion*; Procedia Engineering; 74: 297-302.
4. Okeyoyin, O.A., Owolabi, G.M. (2013). *Application of Weakest Link Probabilistic Framework for Fatigue Notch Factor to Turbine Engine Materials*. World Journal of Mechanics; 3: 237-244.
5. G.M. Owolabi and H.A. Whitworth (2013). *Microstructually Small Crack Formation and Growth in Notched Turbine Engine Materials*. JP Journal of Solid and Structures; 7(1): 1-26.
6. G.M. Owolabi and H.A. Whitworth (2013), *On the Concept of Fatigue Notch Factor*. JP Journal of Solids and Structures; 6 (2-3): 63-88.
7. Gbadebo Owolabi, Benedict Egboiyi, Li Shi and Horace Whitworth (2011). *Microstructure-Dependent Fatigue Damage Process Zone and Notch Sensitivity Index.* International Journal of Fracture; 170(2): 159-173.

Conference Presentations and Proceedings

8. G.M.Owolabi and H.A. Whitworth (2011). *A New Extreme-Value Probabilistic Framework for Predicting Fatigue Crack Initiation Life of Notched Components.* Proceedings of the ASME International Mechanical Engineering Congress and Exposition**,** IMECE-2011, November 11-17, 2011, Denver, Colorado, USA: 10 pages.
9. G.M. Owolabi, B. Egboiyi, H.A. Whitworth and O. Aluko (2012). *On Fatigue Strength Reduction Factor, State-of-the-Art,* Proceedings of the ASME International Mechanical Engineering Congress and Exposition**,** IMECE-2012, November 5-11, 2012, Houston, Texas, USA: 10 pages.
10. L. Shi, G.M. Owolabi and R. Prasannavenkatesan (2012), *Microstructurally Small Crack Formation and Growth in Notched Component with Non-Metallic Inclusions.* Proceedings of The Canadian Society for Mechanical Engineering International Congress 2012 CSME International Congress 2012 June 4-6, 2012, Winnipeg, Manitoba, Canada, 7 pages.
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12. Okeyoyin, O.A., Owolabi, G.M. (2013). *Application of Weakest Link Probabilistic Framework for Fatigue Notch Factor to Turbine Engine Materials*. 13th International Conference on Fracture, Beijing China, June 16-21, 2013.
13. Gbadebo Owolabi, Oluwamayowa Okeyoyin, Oluwakayode Bamiduro, Horace Whitworth (2014). *Extension of a Probabilistic Mesomechanics Based Model for Fatigue Notch*

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14. Gbadebo Owolabi, Oluwamayowa Okeyoyin, Oluwakayode Bamiduro, Horace Whitworth (2014), *Fatigue Strength Reduction Factor for Polycrystalline Nickel Base Superalloy with and without Non-Metallic Inclusion*. XVII International Colloquium "Mechanical Fatigue of Metal, Verbania, Italy, June 25-27, 2014.

7. Graduate Students Involved During the Project Period

a. *Students that obtained Graduate Degrees*
   1. Li Shi: (MS Thesis-Completed, May 2012): Microstructurally Small Crack Growth Modeling in Notched Components with Non-Metallic Inclusions
   2. Benedict Egboiyi: (MS Thesis-Completed, May 2012): Extreme-Value Probabilistic Method for Estimating Microstructure-Dependent Fatigue Notch Factor
   3. Mayowa Okeyoyin: (MS Thesis-Completed, December 2013): Probabilistic Mesomechanics-Based Methods for Fatigue Life Prediction of Turbine Engine Materials

b. *Other Graduate Student Participated in the Project in many different forms including assisting in lab, implementing codes and computer lab support*

   Daniel Odoh
   Kieron Bradshaw
   Ravi Jaglah
   Lekan Adewuyi
   Mathew Osagie
   Atiba Brereton
   Adewale Olasumboye
   Denzell Bolling

c. *Undergraduate Student*

   Victoria Adejumo
   Rufus A Peterson
   Kashta Rennie
   Liu Jones
   Alexanderia Poole

8. Awards, Honors and Appointments

- George David/ United Technology Corporation Assistant Professor (2012-Date)
- Tau Beta Pi Engineering Honor Society, April 2014.
- Chaired *"Fatigue Failure in Engineering Materials and Structures"* for the ASME International Mechanical Engineering Congress and Exposition**,** IMECE-2012-IMECE-2014.

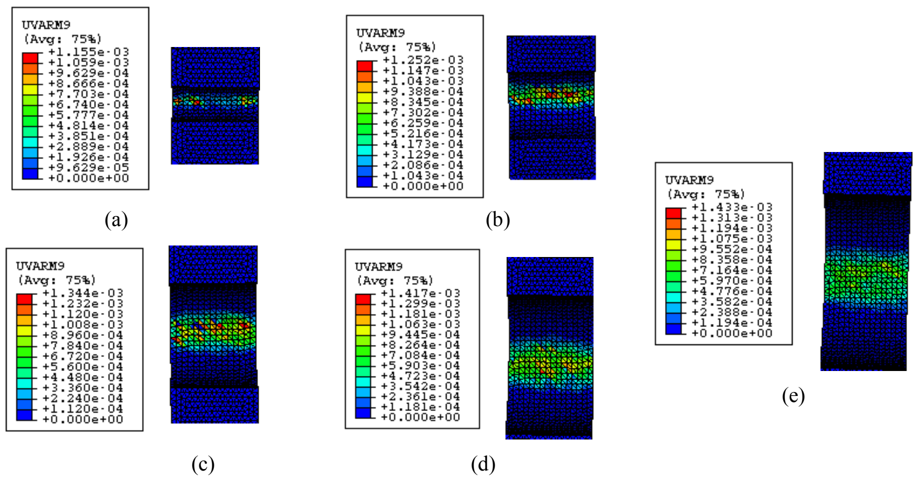

Fig. 1: Plastic strain distributions within the notch root region of a double-edge notched plate (at the same strain amplitude of $\varepsilon_y = 0.027$ % and strain ratio $R_\varepsilon = -1$) for various notch root radii ρ considered (a) 200 μm (b) 400 μm (c) 600 μm (d) 800 μm (e) 1000 μm.

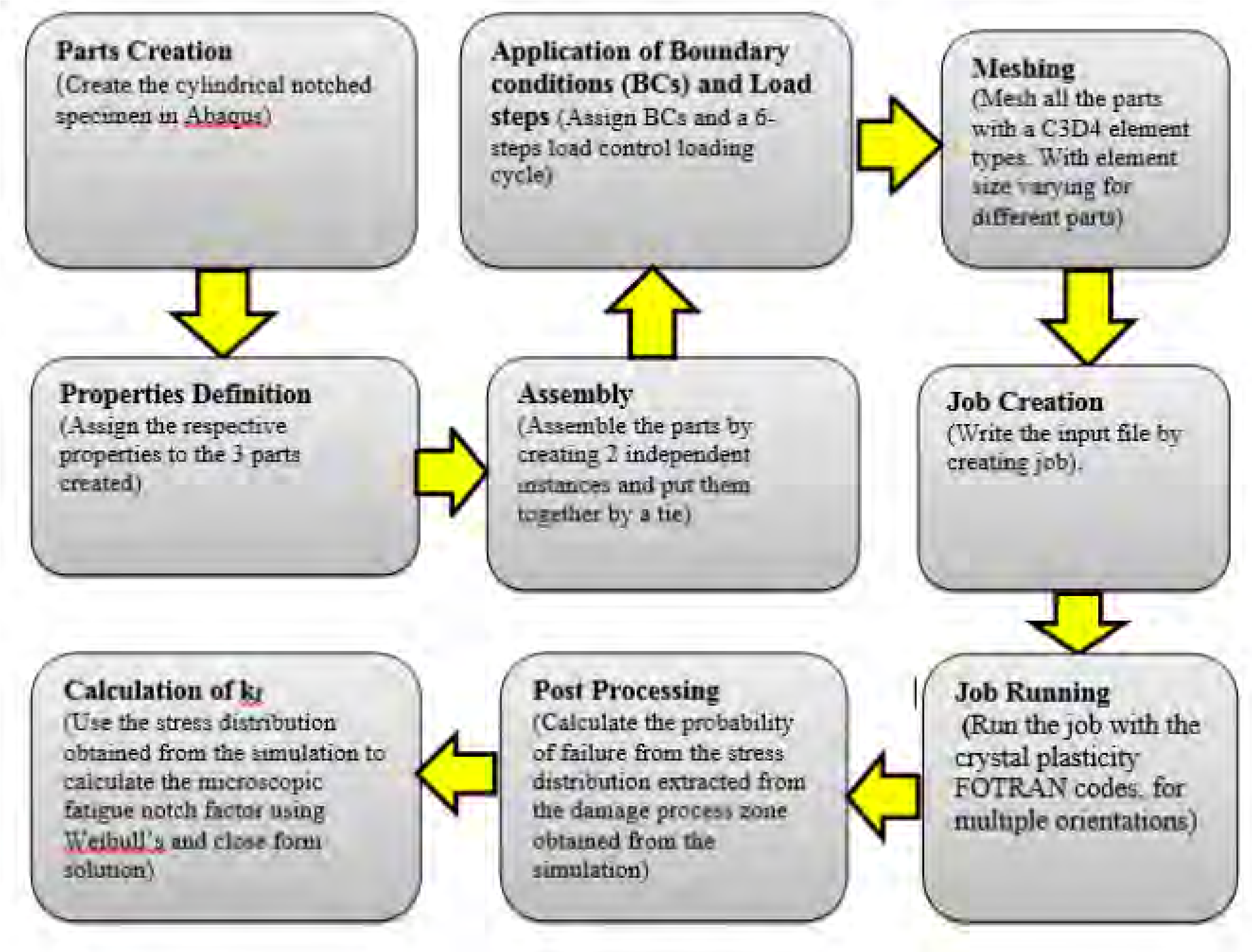

Fig. 2: Flow chart of the finite element modeling and simulation strategy.

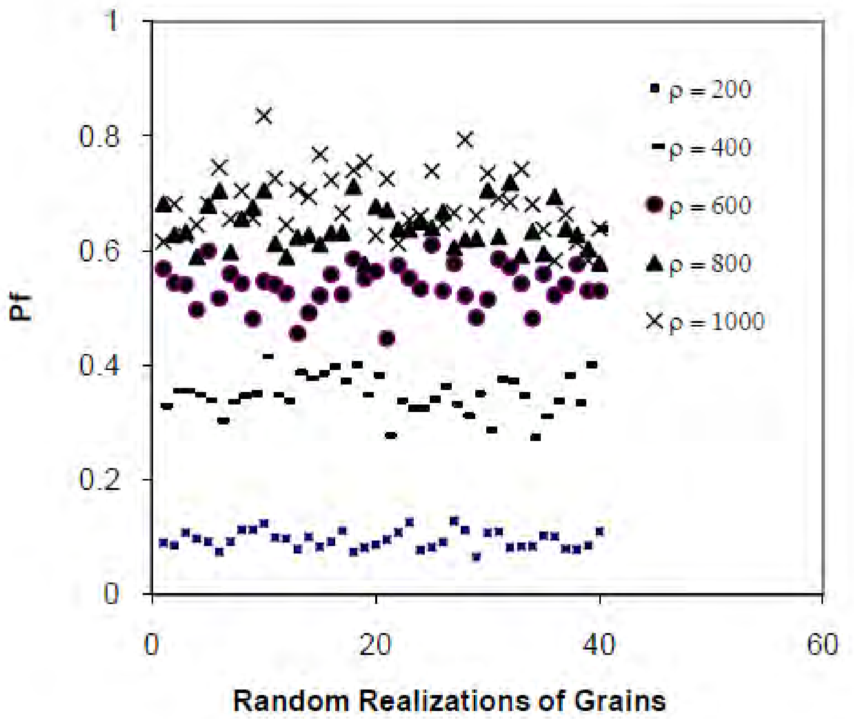

Fig. 3: Probability of fatigue crack initiation for 40 random realizations of grains at the same strain amplitude of 0.027 % for notch root radii ranging from 200 μm to 1000 μm, with the upper bound trend line superimposed.

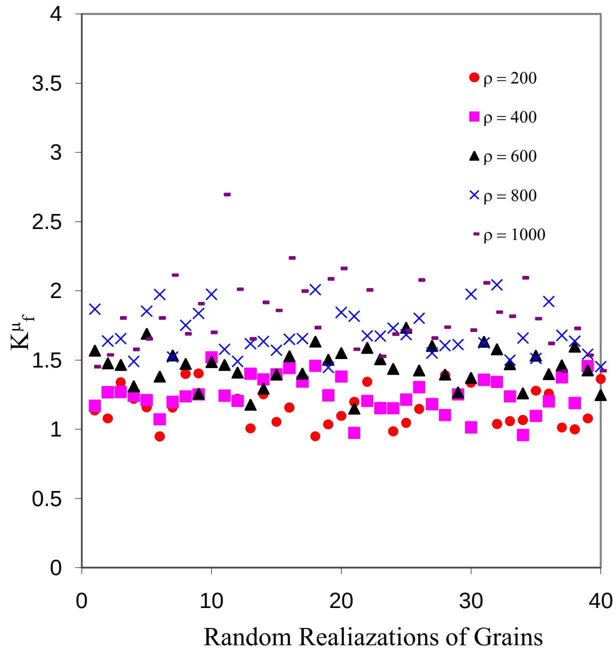

Fig. 4: Distribution of the fatigue notch factor, K_f^{μ} at the same strain amplitude of 0.027% for notch root radii ρ ranging from 200 μm to 1000 μm for 40 random realizations of grains.

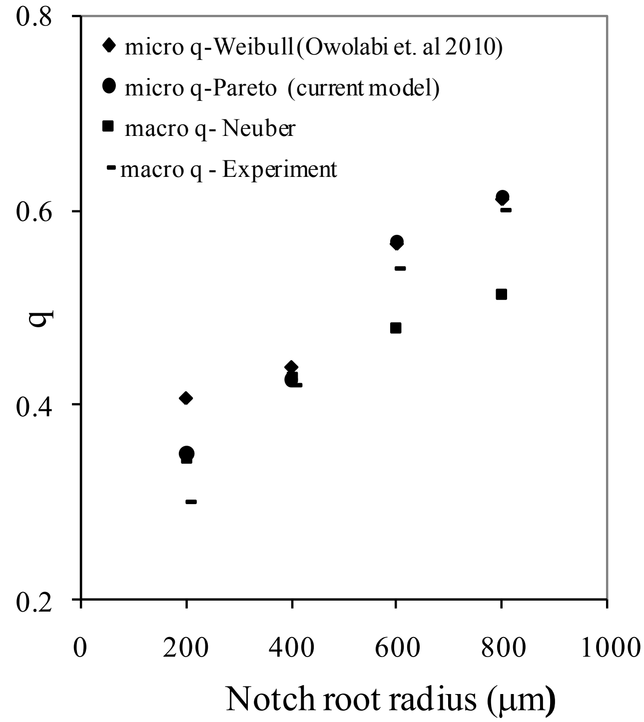

Fig. 5: The dependence of notch sensitivity index on notch root radius comparing measures of q based on K_f^{μ} and experimentally determined conventional K_f for OFHC Cu, based on the ratio of un-notched to notched fatigue strengths at long lives.

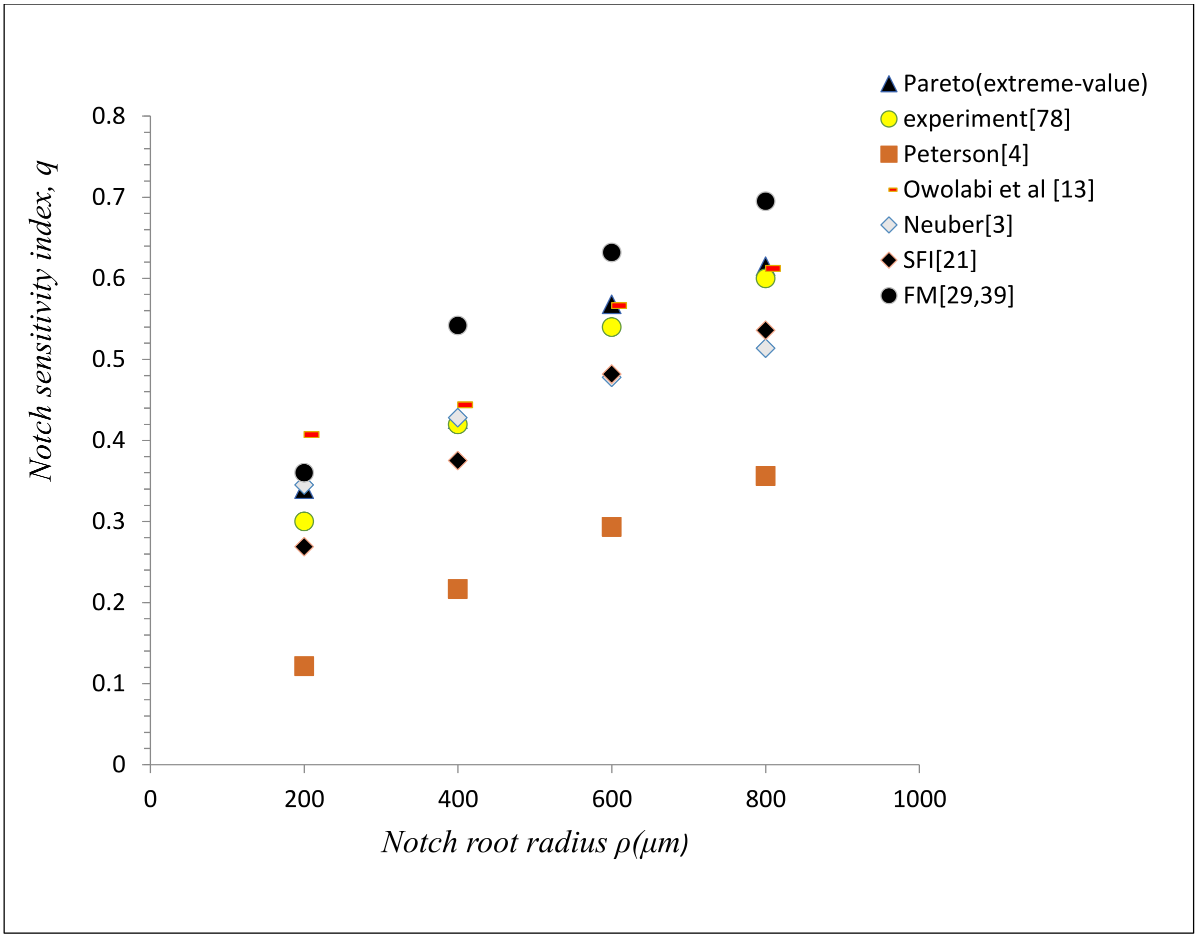

Fig. 6: Comparison of the fatigue notch sensitivity obtained by different models to the experimentally determined conventional fatigue notch factor for OFHC Cu, based on the ratio of un-notched to notched fatigue strengths at long lives.

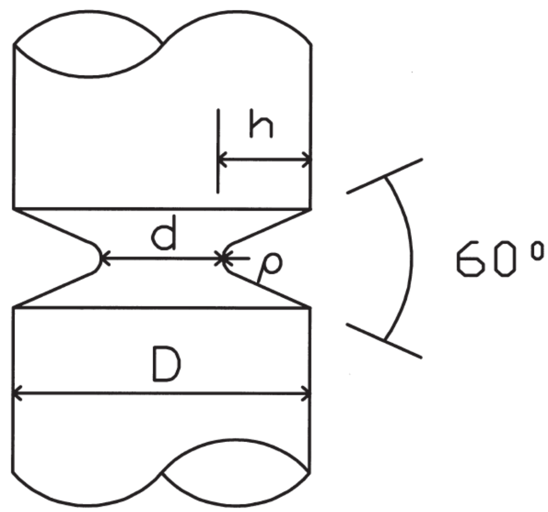

Fig. 7. Gage section of the cylindrical specimen with a circumferential V-notch.

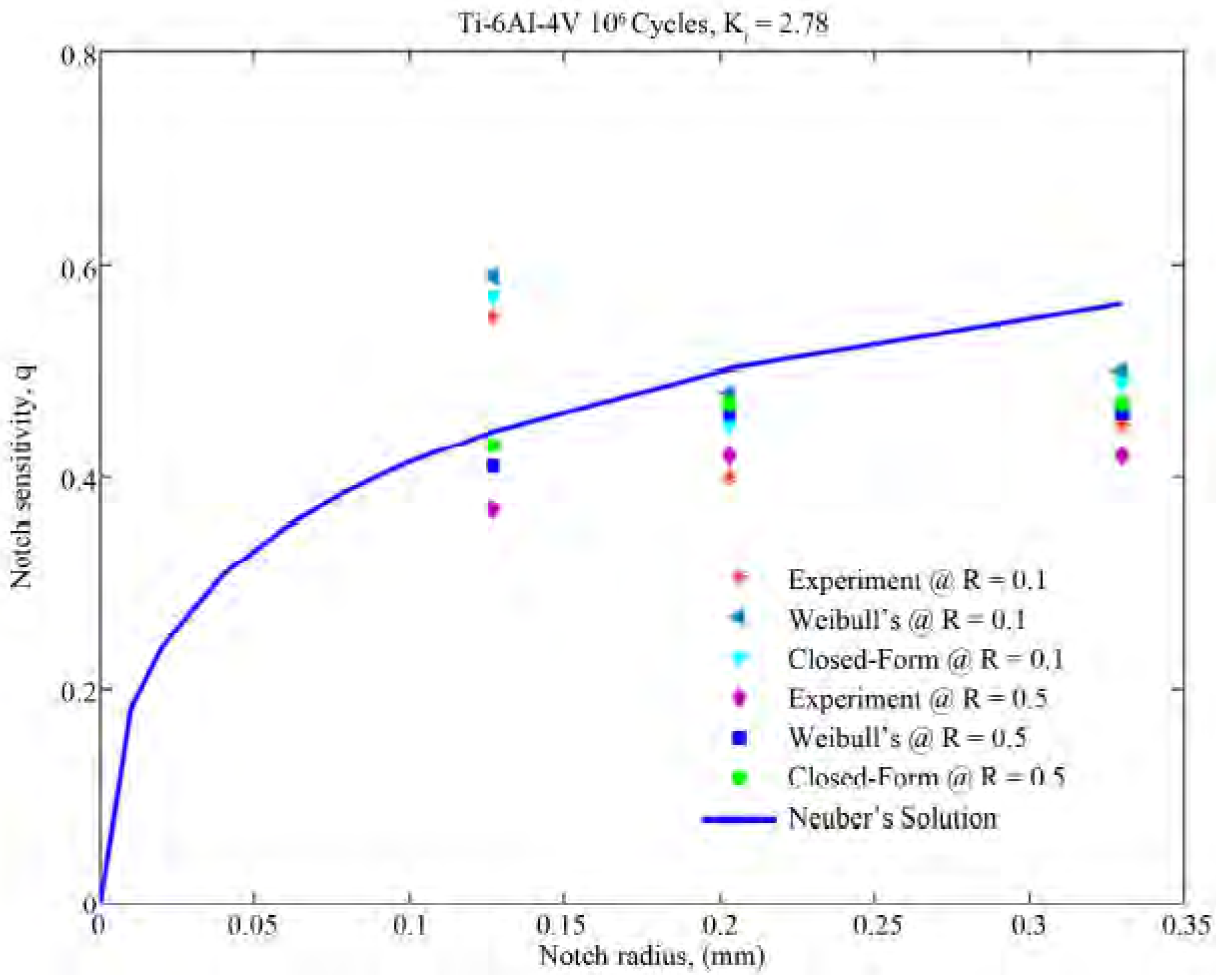

Fig. 8: Notch sensitivity versus notch root radius for three notch sizes.

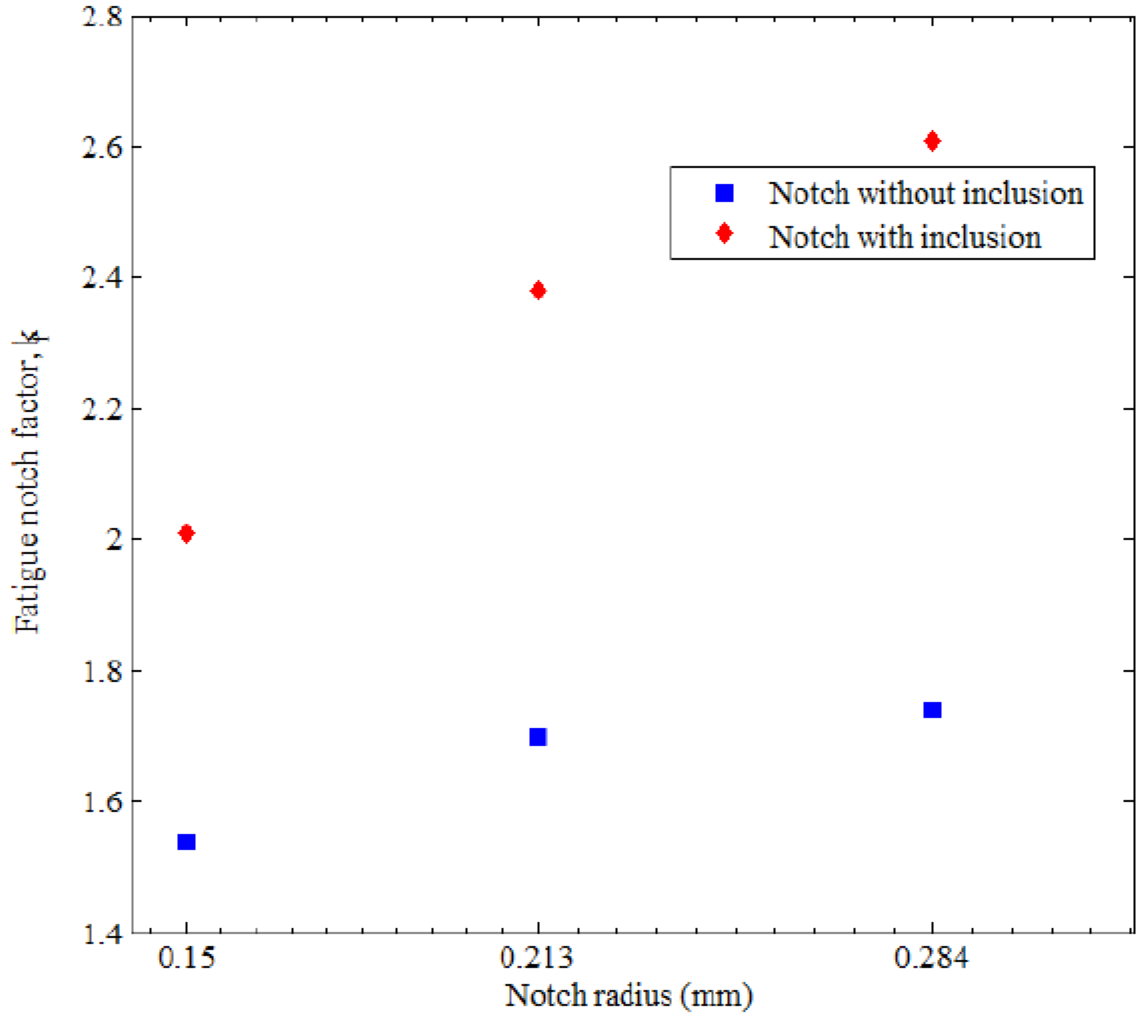

Fig. 9: Fatigue notch factor vs. notch root radius for notched nickel base superalloy with and without inclusion.

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Table 1. Comparison of measured and predicted K_f using the new framework and closed form analysis

Test Case	K_t	Notch radius, $\boldsymbol{\rho}$ (mm)	Notch depth, h (mm)	R-ratio	Experimental average K_f	K_f using Weibull's weakest link	K_f using closed-form analysis
1	2.78	0.330	0.729	-1	2.79	2.73	2.66
2	2.78	0.330	0.729	0.1	1.80	1.89	1.88
3	2.78	0.330	0.729	0.5	1.75	1.82	1.84
4	2.78	0.203	0.254	0.1	1.71	1.86	1.80
5	2.78	0.203	0.254	0.5	1.74	1.83	1.83
6	2.78	0.127	0.127	0.1	1.98	2.05	2.01
7	2.78	0.127	0.127	0.5	1.65	1.72	1.77